Measurement Methods

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Low Cost, Accurate Monitoring of Indoor Carbon Monoxide Concentrations

B. Croxford[a] L. Fairbrother[b]

[a]Bartlett School of Graduate Studies, University College London
[b]Learian Environmental Ltd, Ashwood House, Yateley, Hants

Key Words
Carbon monoxide · Low cost · Datalogger

Abstract
This paper reports on the ICOM carbon monoxide monitoring device, this is a low cost, highly accurate, data logger. In the default setting it monitors carbon monoxide (CO) every minute and stores an average CO reading every 15 minutes. Air temperature is also recorded. The logger is physically small, approximately the size of 2 cigarette packets, it is rechargeable and requires no programming to start, just switching on. The technology behind the logger is similar to that used in the StreetBox monitoring instrument, which was developed from a prototype made by the author and used in various research projects [1,2]. This paper describes the monitoring device and reports briefly on a case study where 80 of the loggers were used to monitor CO in homes at risk from high CO concentrations. The ICOM logger has been shown to be accurate and the inter-instrument variation to be within 0.2 ppm at low concentrations and ±5% at higher concentrations.

Introduction

This paper reports on a novel small, low cost, highly accurate, data logger for carbon monoxide. It has been developed based on technology that arose from an EPSRC[1] funded research project started in 1994. In this project the author was required to find a method to measure "air pollution" at a number of urban locations to compare pollution concentrations with spatial layout. In 1994 the only approved method for measuring CO was with the non-dispersive infra-red (NDIR) absorption technique. For the current work this was too expensive, physically it was too large and it required too much power to be able to be used in a small standalone device – so a different approach was taken.

The project required measurements of "air pollution" at multiple locations monitored frequently, accurately and at low cost. CO was chosen as a proxy measure for "air pollution" as in urban areas as much as 90% of CO in ambient air comes from motor vehicles [3]. In 1998 transport was estimated to be the source of 74% of all UK CO emissions [4].

[1]Engineering and Physical Sciences Research Council, www.epsrc.ac.uk.

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Dr B. Croxford
Bartlett School of Graduate Studies
1–19 Torrington Place, University College London, London WC1E 6BT, UK
Tel. +44 (0) 20 7679 1890. Fax +44 (0) 20 7916 1887.
E-Mail b.croxford@ucl.ac.uk

Many reports have linked air pollution and health problems, some, but not all, have linked CO to particular health effects. A recent review of the effects of air pollution on health gives evidence that links CO exposure to congestive heart failure (CHF) [5]. A more recent time series study, however, found no association between daily levels of any pollutant and daily hospital admissions for CHF [6], they suggest this may be due to limited statistical power and misclassification, they also present a summary of other studies that have found links with CO and health problems.

During the EPSRC funded research project reported in [1], dataloggers were produced and used to measure external concentrations of CO. The sensing method chosen employed electrochemical fuel cells produced under the name "A3CO EnviroceL" [7]. The author processed the data from these sensors to achieve accurate results when tested against NDIR monitors that were part of the government funded monitoring network. These dataloggers were able to provide accurate, simultaneous, unattended and relatively cheap measurements of CO at multiple locations. An important part of the design was to ensure that operatives could easily install these monitors, they were thus designed to be as light as possible and could be fixed to street furniture such as lamp posts with a simple fixing device. Initial versions were solar powered however these were problematic in summer because trees reduced sunlight. Current commercial versions are low power and use rechargeable batteries.

Subsequent projects used the same loggers to measure CO concentrations in naturally ventilated offices and homes with gas cookers. During the course of these projects approaches were made by Learian Ltd and other colleagues that led to Learian requesting licensing of the original technology from UCL. However, obsolescence of one of the key components forced a change in design and led to the development of the new Learian StreetBox.

The prototype StreetBox used in the research projects by Croxford, required significant development by Learian to become the commercial Learian StreetBox. This equipment is now in use by UK local authorities as a screening tool for help in monitoring Air Quality Management Areas [8].

The strong links developed between the authors over the years have helped both parties and thanks to a successful grant application to the Department of Health, it was possible for UCL to commission Learian to develop the next generation of CO datalogger suitable for unobtrusive indoor monitoring purposes.

This project titled "Neuropsychological Effects of Low Level Exposure to Indoor Carbon Monoxide", was led by the Medical Toxicology Unit at Guys and St Thomas's Hospital. It aimed to monitor a large number of homes to find if individuals with exposure to relatively high levels of CO had measurable differences in neuropsychological function compared to people with low exposure. In the first winter of measurement 56 homes were monitored, some of the results from this study are presented in this paper, a future paper will report fully [9].

It was known that the cost of development was the main barrier preventing the miniaturisation of the original StreetBox technology. This project provided the opportunity to produce the ICOM minilogger. The original brief to Learian was to monitor low levels of CO (0.5–500 ppm) accurately, to sample every minute or faster, and to provide averages every 15 minutes for 3 weeks. The logger had to be as small as possible and as light as possible, completely silent, self-contained and extremely simple to use. The memory had to have a separate battery backup for when the rechargeable battery had run out of power. Including the post-processing software that was required to compensate for lack of processing power on the miniloggers themselves, the cost per logger then reduced to less than £300 for an order of 120.

Materials and Methods

The solution Learian developed was named the ICOM minilogger. This can provide high accuracy data logging of real time values of CO and air temperature. It is fully self-contained with a rechargeable battery and will gather real time data continuously: see Table 1 for specifications. The sensor used is the Citicel A3CO from City Technology [7], the differences in specification between

Table 1. Specifications of ICOM minilogger

Dimensions	110 × 80 × 42 mm
Weight	550 g
Typical maximum monitoring duration	35 days
Sensor used	CityTech A3E/F
Expected sensor operating life	2 years
Maximum range (sensor)	0–500 ppm
Resolution (sensor)	0.1 ppm
Maximum zero shift (ICOM)	0.5 ppm equivalent
Temperature range (sensor)	−20 to +50°C
Pressure range (sensor)	Atmospheric ±10%
RH range (sensor)	15 to 90% non-condensing
Long-term output drift (sensor)	<10% of signal loss/year in air
Repeatability (sensor)	<1% of signal

the sensor and the minilogger are due to the proprietary techniques developed by Learian.

The logger was designed to be deployed by building surveyors and needed to be as simple as possible to operate. The solution to this was a simple on/off switch. The equipment is configured to self-start and log data from the time it is switched on to the moment it is downloaded.

The building surveyors were trained to select monitoring positions in homes that corresponded to a specified set of criteria. Since the aim of the monitoring was to measure occupants' exposure to CO, the ideal monitoring position was considered to be at the head height of a seated individual in a representative position in the main living area of the dwelling. The surveyors were also asked to make sure that the logger was as far from both sources of CO and draughts as possible and also out of direct sunlight. Most importantly they also had to ensure that the logging position was acceptable to the occupants. It was thus important that the logger was as small and as unobtrusive as possible.

A further consideration was occupant feedback, this logger has no lights and makes no sound, as such, and no real time information on CO concentrations is given to the user. This was an important consideration, the project went through ethical approval and had a procedure that was designed to identify "at risk" homes and act immediately if necessary to provide occupants with methods of dealing with CO if concentrations breached World Health Organisation guidelines [10].

The process for monitoring CO for this project was as follows; each surveyor was sent, via registered post, a box of either 10 or 20 miniloggers. Each logger had been charged and checked before posting. The surveyors were also sent a pre-paid return box for 5 or 10 loggers. On visiting a home eligible for monitoring (that fitted the criteria of the project) the surveyor would select a monitoring position and switch the logger on. Three weeks later the surveyor would collect the logger, switch it off and when sufficient loggers had been collected would post them all back to the project co-ordinator.

The project co-ordinator would download the data using a simple terminal emulator program and the custom cable to the RS-232 port. This process takes a few minutes to download the entire memory into a text file.

In order to reduce the cost and size of the minilogger, some of the processing power has been taken out of the logger itself and instead the resulting text files need to be run through a calibration program which applies proprietary algorithms to clean the data, for example occasional spikes caused by electrical interference. This program also acts as an archive for data, storing all data from all loggers in a protected Microsoft access database. From this database, the data can then be exported to Excel and used for analysis.

The results from two recent projects have provided repeatability, resolution and accuracy data. Twelve loggers were used in a calibration exercise to test repeatability of the miniloggers and also show resolution and accuracy of the logger. The loggers were placed in 3 rows of 4 in the test chamber in phase 1 and then in the same formation in an office in central London. In the test chamber the loggers were exposed to a source of CO.

Results

During the course of the project "Neuropsychological Effects of Low Level Exposure to Indoor Carbon Monoxide", reported in [9] one location clearly had very low CO concentrations, see Figure 1, indicating no indoor sources of CO. The 15-minute averages from the ICOM were aggregated to 1-hour averages to allow comparison with the closest automatic urban network (AUN) monitoring location at Birmingham Centre [11]. By eye it can be seen that the measurements are very close despite the fact that the location of the ICOM monitor was in a home 10 km from the AUN monitor itself. The r^2 correlation coefficient was 0.42, mean ICOM CO concentration was 0.60 ppm and mean Birmingham Centre AUN CO concentration was 0.55 ppm, the ICOM reading was 9% higher perhaps reflecting errors but also local effects. The mean absolute distance (root mean square or RMS error) from Birmingham Centre AUN results was 0.06 ppm, (standard deviation 0.15 ppm).

Two separate experiments, one low exposure and one with higher CO exposure were carried out with 11 and 12 ICOM loggers respectively. Figure 2 shows the results from the low exposure experiment. The close match of the data from individual ICOM loggers shows that even at very low concentrations of CO, they are accurate to ±0.2 ppm. Further analysis shows that the mean distance (RMS) from the overall mean of all ICOM loggers is within 0.13 ppm, see Table 2, with a typical standard deviation of these distances of 0.06 ppm.

Figure 3 presents the results of the high exposure CO experiment. In this case 12 loggers were exposed to CO levels of around 12 ppm. Again there is a strong correlation between loggers. All mean ICOM measurements were within ±5% of the mean with the typical standard deviation of these differences being 1.6%, see Table 3.

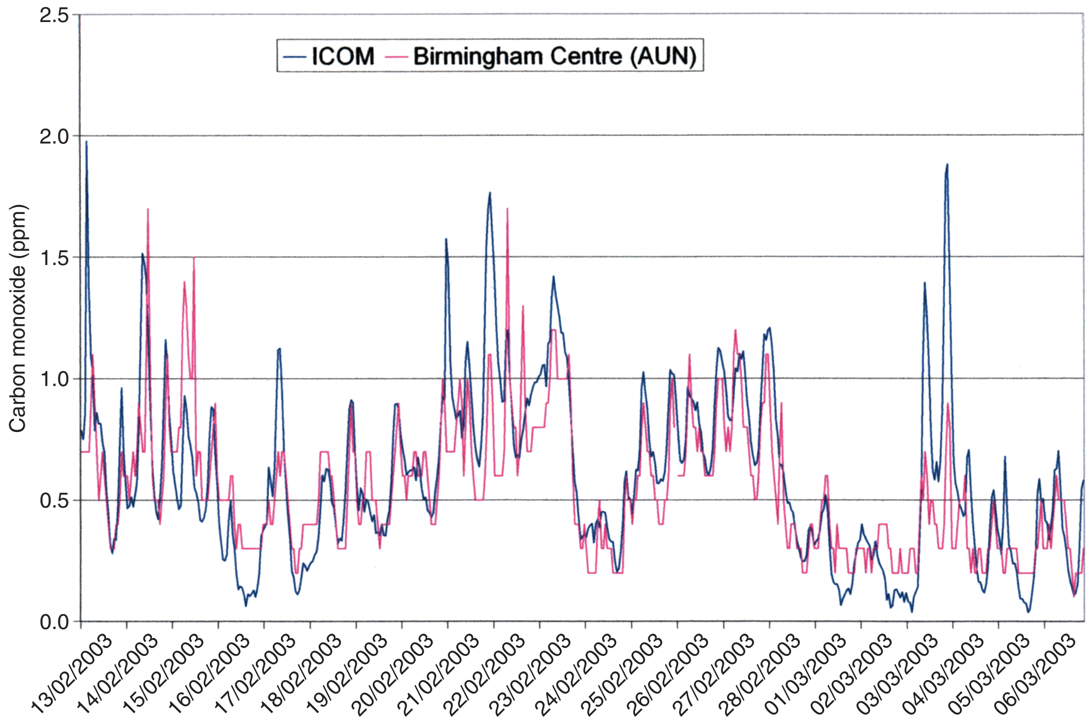


Fig. 1. Results from 3 weeks monitoring in Birmingham.

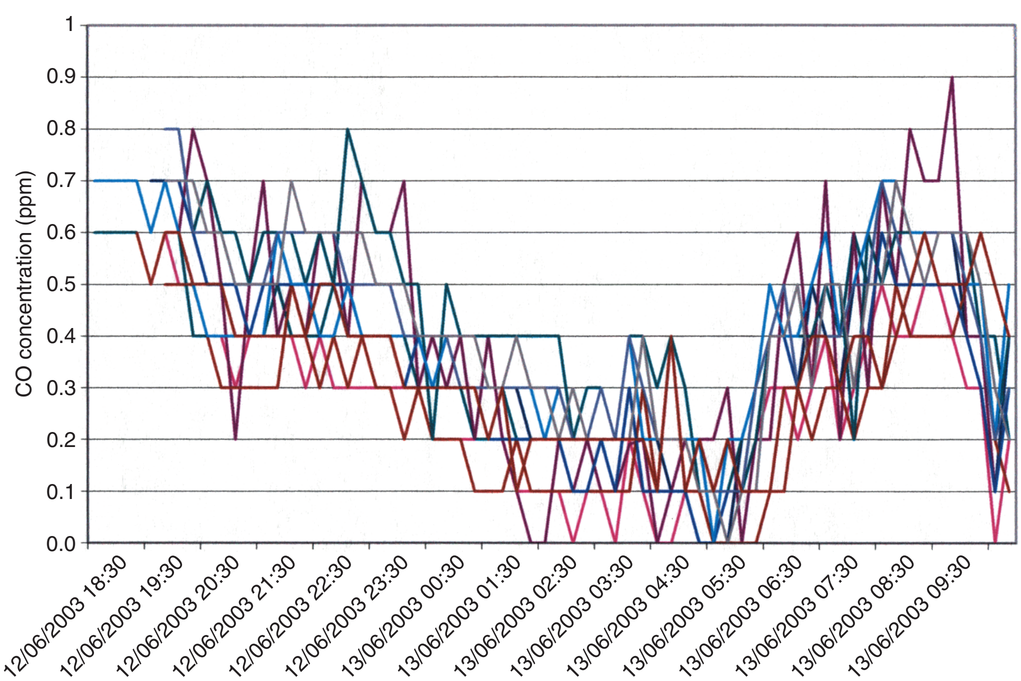
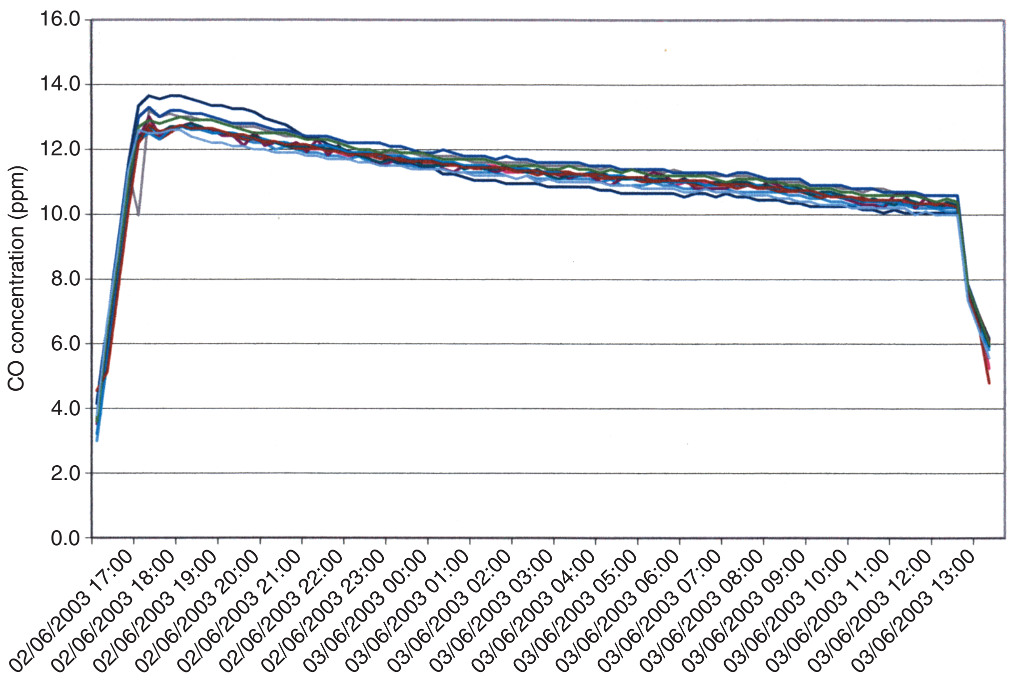


Fig. 2. Monitoring low levels of CO; results from 11 loggers superimposed.

Table 2. Results from low exposure experiment

ICOM	Mean CO (ppm)	RMS difference from mean (ppm)	SD RMS difference (ppm)
ICOM 10	0.37	0.05	0.06
ICOM 15	0.25	0.12	0.04
ICOM 2	0.36	0.05	0.05
ICOM 3	0.39	0.12	0.07
ICOM 41	0.25	0.13	0.07
ICOM 50	0.45	0.10	0.07
ICOM 90	0.34	0.05	0.04
ICOM 9	0.41	0.06	0.06
ICOM 88	0.41	0.06	0.04
ICOM 86	0.41	0.08	0.05
ICOM 73	0.34	0.08	0.07
Total Mean	0.36	0.08	0.06

Fig. 3. Monitoring high levels of CO; results from 12 loggers superimposed.



The results show how the ICOM logger can measure accurately at very low ambient levels of CO and that readings from different co-exposed ICOM loggers are very close.

Discussion

The results obtained need to be compared to the applications in which the ICOM logger might be used. It is important to note that when carrying out monitoring campaigns, the precise location of the monitor will affect the concentration of the monitored variable. It is almost always impossible to monitor in the perfect monitoring position due to a variety of logistical reasons. The ICOM was designed to monitor accurately concentrations of CO in people's homes. The design can be considered a success whilst it is a compromise between competing criteria.

The logger is small enough to be unobtrusive and able to be positioned in a location that does not affect the behaviour of the occupants. It is light enough for many

Table 3. Summary results from the high exposure experiments

ICOM	Mean CO (ppm)	RMS difference from mean (%)	Std Dev RMS diff (%)
ICOM 10	11.0	3.55	2.43
ICOM 15	11.0	0.83	1.10
ICOM 2	11.3	2.77	1.97
ICOM 20	10.9	1.40	1.90
ICOM 3	11.0	1.07	0.95
ICOM 41	11.1	0.75	1.29
ICOM 50	11.0	0.86	1.21
ICOM 90	11.4	3.24	0.65
ICOM 9	11.0	1.01	1.54
ICOM 88	11.0	1.32	3.53
ICOM 86	11.2	2.06	0.97
ICOM 73	10.8	2.34	1.53
Overall Mean	11.1	1.8	1.6

loggers to be easily carried by a single surveyor, and for many to be posted relatively cheaply. It is simple enough to use that operating errors are kept to a minimum. It is silent, so does not disturb the occupants. It has sufficient battery power to last for a month of monitoring and most importantly it has sufficient processing power to provide very accurate results.

The ICOM does require that the raw data is processed with the ICOM software before this accuracy can be achieved, while this is not ideally convenient it does have the benefit of quality control and can add a layer of consideration before the CO measurements can be acted upon. If neither the researcher nor the occupant know the CO concentration at the time of measurement, there are no ethical consequences of the researcher failing to act to reduce CO levels. If, after analysis, high levels of CO are found then is the time for appropriate action to be taken immediately.

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